Systems Engineering Cost Estimation for Space Systems

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The applicability of COSYSMO, a systems engineering cost model, is explored in the context of space systems through the analysis of two main assumptions. First, the WBS elements of the model are mapped to a prototypical WBS for space systems. Second, the life cycle phases assumed in the model are mapped to the phases outlined in the latest National Security Space acquisition policy. Through the analysis of these assumptions, the applicability of COSYSMO to space systems can be improved. Moreover, techniques for performing partial estimation of systems engineering by systems engineering activity and life cycle phase are provided to further the applicability of COSYSMO to space systems.

Nomenclature

CER	= Cost Estimating Relationship
COSYSMO	= Constructive Systems Engineering Cost Model
DoD	= Department of Defense
EIA/ANSI	= Electronic Industries Alliance/American National Standards Institute
INCOSE	= International Council on Systems Engineering
ISO/IEC	= International Standards Organization/International Electrotechnical Commission
MESSOC	= Model for Estimating Space Station Operation Costs
NSS	= National Security Space
SMC	= Space and Missile Systems Center
SSCM	= Small Satellite Cost Model
USCM	= Unmanned Satellite Cost Model
WBS	= Work Breakdown Structure

I. Introduction

SYSTEMS engineering continues to play a critical role in the design and operation of space systems. Despite the role of systems engineering in ensuring mission success, estimating the costs of systems engineering has not reached the same level of maturity as its end item counterparts (i.e., hardware and software). Traditionally, industry and government have bundled the costs of systems engineering with other program management, test, and integration costs; this approach causes two problems. First, it does not allow for sufficiently quantifiable justification for assigning systems engineering costs to space systems; the absence of such justification can prevent programs from adequately staffing the systems engineering resources. Second, it fails to consider the technical and programmatic drivers that have an impact on systems engineering cost, instead relying on estimation techniques that lack the necessary repeatability, fidelity, and objectivity. However, with the recent development of the parametric

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cost model COSYSMO, cost estimating relationships are now available to provide the necessary quantifiable justification for systems engineering costs.

In the past, systems engineering resources were calculated as a function of the total system costs. Models such as MESSOC were used to estimate the operations costs for the space station but bundled systems engineering under numerous categories such as "other integrated logistic support" and "user integration operations".[1] Others used models such as SSCM to estimate the total cost of a satellite system as a function of characteristics such as power and aperture, but found these models to be limited for distributed satellite systems.[2] This paper provides a detailed analysis of a systems engineering cost model, COSYSMO, and how its activities and life cycle phases can be adjusted to apply to space systems. Furthermore, a technique for partial estimation of systems engineering is provided which aids in the estimation of space systems engineering activities based on the needs of today's acquisition contracts.

A. COSYSMO

COSYSMO is a model that can help people reason about the economic implications of systems engineering on projects. Similar to its predecessor, COCOMO II[3], it was developed at the University of Southern California as a research project with the help of The Aerospace Corporation, BAE Systems, Boeing, General Dynamics, L-3 Communications, Lockheed Martin, Northrop Grumman, Raytheon, and SAIC. Following a parametric modeling approach, COSYSMO estimates the quantity of systems engineering labor, in terms of person months, required for the conceptualization, design, test, and deployment of large-scale software and hardware projects. By utilizing COSYSMO, the user has the ability to make proposal estimates, investment decisions, budget planning, project tracking, tradeoffs, risk management, strategy planning, and process improvement measurements.

B. Assumptions of the Model

One of the central assumptions of COSYSMO is the systems engineering WBS, which defines a standard set of 33 systems engineering activities. The WBS is derived from the standard EIA/ANSI 632 *Processes for Engineering a System* which is listed in Table 1.[4] Before the space community can adopt COSYSMO, it must consider the differences between the WBS provided in EIA/ANSI 632 and a typical systems engineering WBS for space systems. A prototypical WBS for space systems, from the USCM model, is provided in Figure 2. A comparison between the two WBSs is provided in Figure 3.

The second assumption is the life cycle which is derived from the standard ISO/IEC 15288 *Systems Engineering — System Life Cycle Processes.*[5] The life cycle phases in this standard are compared to the mandated acquisition life cycle defined by the DoD in NSS policy 03-01.[6] It is expected that the findings from this study will reveal the necessary adjustments for successful incorporation of COSYSMO into the space domain.

II. Previous Work on Systems Engineering Standards

Created in 1969, U.S. MIL-STD 499A provided the first definition of the scope of engineering management.[7] In 1985, MIL-STD 490-A followed and provided additional guidance on the process of writing system specifications for military systems.[8] These standards were influential in defining the scope of systems engineering in their time. More recently, the standard ANSI/EIA 632 *Processes for Engineering a System* provides a typical systems engineering WBS. This list of activities was selected as the baseline for defining systems engineering in COSYSMO. The standard contains five fundamental processes and 13 high-level process categories that are representative of systems engineering organizations. The process categories are further divided into 33 activities as shown in Table 1.

Figure 1 shows the systems engineering effort profile obtained from expert opinion and historical data provided by aerospace companies such as Northrop Grumman, Lockheed Martin, and Boeing.[9]

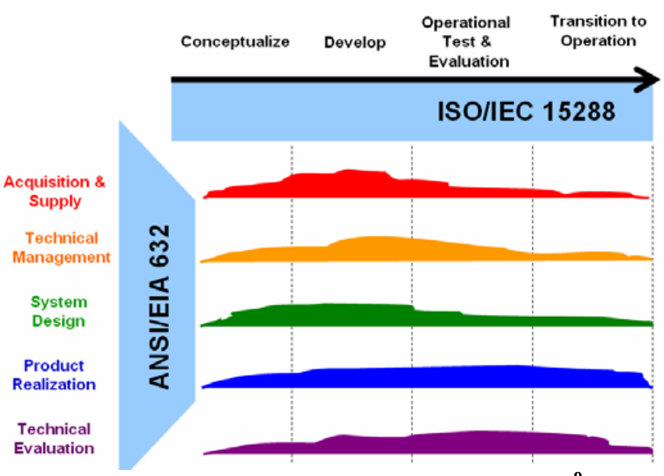

Figure 1. Systems Engineering Effort Profile[9]

III. Systems Engineering Activities

This section provides a comparison of the systems engineering activities included in COSYSMO and a suggested set of systems engineering activities that can be adopted for estimating space systems. It is also shown how systems engineering activities can be partially estimated depending on the scope of the project.

A. COSYSMO Work Breakdown Structure (EIA/ANSI 632)

The EIA/ANSI 632 standard was developed between 1994 and 1998 by a working group of industry associations, INCOSE, and the DoD with the intent to provide a standard for use by commercial enterprises, as well as government agencies and their contractors. It was designed to have a broader scope than previous systems engineering standards and have less detail. The activities in the model, shown in Table 1, are set in the context of application environment across five process categories: (1) Acquisition and Supply, (2) Technical Management, (3) System Design, (4) Product Realization, and (5) Technical Evaluation.

Table 1. EIA/ANSI 632 Processes and Activities[4]

Fundamental Processes	Process Categories	Activities
Acquisition and Supply	Supply Process	(1) Product Supply
	Acquisition Process	(2) Product Acquisition, (3) Supplier Performance
Technical Management	Planning Process	(4) Process Implementation Strategy, (5) Technical Effort Definition, (6) Schedule and Organization, (7) Technical Plans, (8)Work Directives
	Assessment Process	(9) Progress Against Plans and Schedules, (10) Progress Against Requirements, (11) Technical Reviews
	Control Process	(12) Outcomes Management, (13) Information Dissemination
System Design	Requirements Definition Process	(14) Acquirer Requirements, (15) Other Stakeholder Requirements, (16) System Technical Requirements
	Solution Definition Process	(17) Logical Solution Representations, (18) Physical Solution Representations, (19) Specified Requirements
Product Realization	Implementation Process	(20) Implementation
	Transition to Use Process	(21) Transition to use
Technical Evaluation	Systems Analysis Process	(22) Effectiveness Analysis, (23) Tradeoff Analysis, (24) Risk Analysis
	Requirements Validation Process	(25) Requirement Statements Validation, (26) Acquirer Requirements, (27) Other Stakeholder Requirements, (28) System Technical Requirements, (29) Logical Solution Representations
	System Verification Process	(30) Design Solution Verification, (31) End Product Verification, (32) Enabling Product Readiness
	End Products Validation Process	(33) End products validation

These activities help answer the *what* of systems engineering and helped characterize the COSYSMO model. The EIA/ANSI 632 standard provides a generic industry list that may not be applicable to every situation, but is useful in describing the scope of systems engineering. Other types of systems engineering WBS lists exist, such as the one developed by Raytheon Space & Airborne Systems.[10] Such lists provide, in much finer detail, the common activities that are likely to be performed by systems engineers in those organizations, but are generally not applicable outside of the companies in which they are created. In addition to organization applicability, there are significant differences in different application domains, especially in space systems engineering. Such a comparison is provided for further exploration of COSYSMO relevance in space systems.

B. Space Systems Work Breakdown Structure (USCM)

The Unmanned Space Vehicle Cost Model is a parametric model that provides linear and nonlinear CERs to estimate the costs of satellite development and production.[11] USCM CERs describe bus and communication payload costs, as well as their associated system engineering; program management; and integration, assembly, and test costs. The model includes all satellite buses, but focuses on communication satellite payloads. Non-communication satellite data points are primarily used for their platform/bus costs, and their associated payload costs are captured in the database but not used for CER development. The majority of the costs included in USCM are end-of-program actual costs. SMC published the first USCM edition in 1969. Since that time, it has gone through seven iterations.

The USCM database, currently in its eighth version, includes 12 NASA, 22 military, and 12 commercial programs in its data repository. Of interest in this paper is the WBS assumed in the model, particularly the systems engineering activities as shown in Figure 2.

- 1 Space Vehicle
  - 1.1 Integration, Assembly & System Test
  - 1.2 Spacecraft
    - 1.2.1 Structure, Interstage/Adapter
    - 1.2.2 Thermal Control
    - 1.2.3 Attitude Determination Control System
      - 1.2.3.1 Attitude Determination
      - 1.2.3.2 Reaction Control System
    - 1.2.4 Electrical Power Supply
      - 1.2.4.1 Power Generation
      - 1.2.4.2 Power Storage
      - 1.2.4.3 Power Conditioning and Distribution
    - 1.2.5 Telemetry, Tracking, and Command
      - 1.2.5.1 Transmitter
      - 1.2.5.2 Receiver/Exciter
      - 1.2.5.3 Transponder
      - 1.2.5.4 Digital Electronics
      - 1.2.5.5 Analog Electronics
      - 1.2.5.6 Antennas
      - 1.2.5.7 RF Distribution
  - 1.3 Communications Payload
    - 1.3.1 Transmitter
    - 1.3.2 Receiver/Exciter
    - 1.3.3 Transponder
    - 1.3.4 Digital Electronics
    - 1.3.5 Analog Electronics
    - 1.3.6 Antennas
    - 1.3.7 RF Distribution
  - 1.4 Program-Level
    - 1.4.1 Program Management
    - 1.4.2 Systems Engineering
    - 1.4.3 Data
- 2 Aerospace Ground Equipment
- 3 Launch and Orbital Operations

Figure 2. USCM WBS[11]

Of particular interest are the activities in items 1.4.1 and 1.4.2 since they are analogous to the activities included in COSYSMO. These WBS items are defined as follows[12]:

1.4.1 Program Management
This category includes all effort associated with defining, planning, directing, and controlling company functions, subcontractors, and suppliers in order to accomplish program objectives.

1.4.2 Systems Engineering
This category includes all effort associated with the engineering organization, which allocates and controls the distribution of system-level requirements and specifications to lower level subsystems and equipment items. Also included are costs associated with controlling system-level documents such as specifications, weights, reliability, program equipment units, and quality assurance.

It would appear from the mapping in Table 2 that USCM misses much of the systems engineering effort, but these may be covered in other WBS items such as *1.1 Integration, Assembly & System Test*. It should also be noted that the use of broad statements in the definition of systems engineering activities in the USCM WBS may lead to confusion about what is being included in the model. For example, the use of "all effort associated with the engineering organization" serves as a catch-all term that could include systems engineering. On the other hand, specific activities such as "allocation and control of the system-level requirements" clearly articulate the scope of the effort being covered by the WBS item. To better understand the relationship between EIA/ANSI 632 and USCM, a mapping is provided in Table 2 at an equivalent level of decomposition.

Table 2. Mapping of two Work Breakdown Structures

EIA/ANSI 632 Process Categories	USCM items
Supply Process	1.4.1 Program Management
Acquisition Process	1.4.1 Program Management
Planning Process	1.4.1 Program Management
Assessment Process	1.4.1 Program Management
Control Process	1.4.1 Program Management
Requirements Definition Process	1.4.2 Systems Engineering
Solution Definition Process	1.4.2 Systems Engineering
Implementation Process	1.4.2 Systems Engineering
Transition to Use Process	1.4.2 Systems Engineering
Systems Analysis Process	1.4.2 Systems Engineering
Requirements Validation Process	1.4.2 Systems Engineering
System Verification Process	1.4.2 Systems Engineering
End Products Validation Process	1.4.2 Systems Engineering

This mapping is based on a subjective assessment of the overlap between the 13 detailed process categories in EIA/ANSI 632 and a broad interpretation of WBS items 1.4.1 and 1.4.2 in USCM. At first glance, it is evident that the added detail in the WBS from EIA/ANSI 632 may serve as an advantage, but in practice cost accounting data is not always collected at this level of detail on programs. The WBS in USCM is likely a reflection of the cost accounting practices of the space systems industry over the last 40 years. An additional consideration is that USCM was developed to include NASA, military and commercial space systems which operate under different financial conditions. This presents a challenge for USCM itself: to be detailed enough to be relevant for all space systems but generic enough to be applicable across the diverse types of space systems.

Nevertheless, it is beneficial to understand systems engineering cost at a finer level of granularity, which is at the core of COSYSMO. With this added detail we can estimate the amount of systems engineering effort by systems engineering activity and improve the management and execution of systems engineering in the space domain. The next section shows precisely how to do this.

C. Partial Estimation of Systems Engineering Effort by Activity

The COSYSMO model provides a way to estimate systems engineering effort by WBS element as defined in EIA/ANSI 632. As shown earlier in Table 1, one of the assumptions of the model is that a standard set of systems engineering activities are being performed throughout certain phases in the life cycle. These 33 activities are distributed across five fundamental processes as shown in Table 3. This distribution is not universal but it provides a typical spread of effort that is characteristic of systems engineering projects in the COSYSMO data repository.

Table 3. Systems Engineering Effort Distribution Across ANSI/EIA 632 Fundamental Processes

ANSI/EIA 632 Fundamental Process	Typical effort
Acquisition & Supply	7%
Technical Management	17%
System Design	30%
Product Realization	15%
Technical Evaluation	31%

By utilizing this effort distribution table along with COSYSMO, a user can better allocate the estimated systems engineering resources. To illustrate, assume P_1, P_2, P_3, P_4, and P_5 represent the fundamental processes as shown in Table 3 and x is the single point estimate provided by COSYSMO.

The sum of the five fundamental processes equals the total systems engineering estimate, that is:

$$\sum_{i=1}^{5} P_i = 100\%$$

Therefore, the COSYSMO estimate (x) can be allocated to each of the five processes.

$x * 0.07$ = effort required for P_1
$x * 0.17$ = effort required for P_2
$x * 0.30$ = effort required for P_3
$x * 0.15$ = effort required for P_4
$x * 0.31$ = effort required for P_5

TOTAL = x

The breakdown of effort by systems engineering process is helpful not only for planning purposes but also when an organization is only interested in estimating part of the systems engineering activities. For example, if the systems engineering organization is only responsible for *System Design* (P_3), *Product Realization* (P_4), and *Technical Evaluation* (P_5) then the typical effort can be calculated as a function of the adjusted effort factor as follows:

$P_3 + P_4 + P_5$ = adjusted effort factor
$0.30 + 0.15 + 0.31$ = adjusted effort factor
0.76 = adjusted effort factor

The initial estimate provided by COSYSMO, x, is then adjusted by a factor of 0.76 to reflect the absence of *Acquisition & Supply* (P_1) and *Technical Management* (P_2) activities assumed in the estimate. This case is typical when organizations are contracted to perform a supporting systems engineering function in space systems. However, caution should be taken when using these numbers because they represent an average observed across a range of programs included in COSYSMO. These proportions are likely to change under different circumstances such as a different customer, technical complexity, business process, etc. Organizations are encouraged to derive their own systems engineering effort profile from their historical data following this WBS or one that applies to their way of doing business.

In the same way the systems engineering activities play a significant role in defining the scope of the systems engineering activities covered by COSYSMO, the life cycle phases guide the scope of the estimate as shown in the next section.

IV. Systems Engineering Life Cycle Phases

A. COSYSMO Life Cycle Phases (ISO/IEC 15288)

In 2002, an international effort to define systems engineering life cycle phases yielded the standard ISO/IEC 15288 *Systems Engineering — System Life Cycle Processes*.[5] The standard, developed by the same subcommittee that authored the software standard ISO/IEC 12207, developed the complementary ISO/IEC 15288 augmented with systems engineering expertise. The intent was also to develop a high level, common framework for describing life cycle of systems based on well-defined processes and terminology.

Life cycle models vary according to the nature, purpose, use and prevailing circumstances of the system. Despite an infinite variety in system life cycle models, ISO/IEC 15288 provides an essential set of characteristic life cycle phases that exists for use in the systems engineering domain. For example, the *Conceptualize* stage focuses on identifying stakeholder needs, exploring different solution concepts, and proposing candidate solutions. The *Development* stage involves refining the system requirements, creating a solution description, and building a system. The *Operational Test & Evaluation* stage involves verifying/validating the system and performing the appropriate inspections before it is delivered to the user. The *Transition to Operation* stage involves the transition to utilization of the system to satisfy the users' needs. These four life cycle phases, shown in Figure 3, are within the scope of COSYSMO. The final two were included in the data collection effort but did not yield enough data to be useful in the model calibration. These phases are: *Operate, Maintain, or Enhance* which involves the actual operation and maintenance of the system required to sustain system capability, and *Replace or Dismantle* which involves the retirement, storage, or disposal of the system.

Figure 3. ISO 15288 Life Cycle Phases

Each stage has a distinct purpose and contribution to the whole life cycle and represents the major life cycle periods associated with a system. The stages also describe the major progress and achievement milestones of the system through its life cycle and help answer the *when* of systems engineering and COSYSMO. This assumption is now compared to the mandated acquisition life cycle for DoD space systems.

B. Space System Life Cycle Phases (NSS 03-01)

The National Security Space Acquisition Policy 03-01[6], updated in 2004, highlights the key guidelines and processes associated with the acquisition of DoD space systems. The authority for NSS 03-01 falls under DoD Directive 5000.1 and replaces the processes and procedures described in DoD Instruction 5000.2.[13] Whereas other DoD acquisition policies are focused on the making large quantity production decisions, the NSS acquisition policy provides specific guidance for small quantity high-tech programs which are characteristics typical of space systems. Therefore, the acquisition of space systems follows the acquisition life cycle shown in Figure 4.

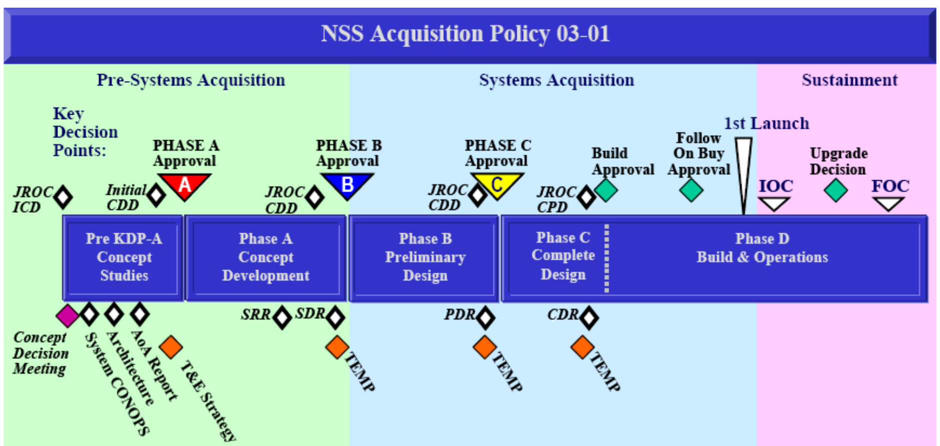

Figure 4. NSS 03-01 Acquisition Phases[6]

The emphasis of the NSS acquisition life cycle phases is on earlier decision points focused on development and launch in contrast to other models which focus on operation & maintenance activities. Key decision points throughout the life cycle contain different entry and exit criteria which are around concept/architecture development, risk reduction, and design development. For traceability of legacy life cycle, the mapping between DoD 5000 and NSS 03-01 is provided in Table 4.[14] Additionally, we provide a third column including the ISO/IEC 15288 life cycle phases.

Table 4. Acquisition Phase Name Comparison (adapted from[14])

DoD 5000[13]	NSS 03-01[6]	ISO/IEC 15288[5]
Pre-acquisition activities Requirements document, Concept of Operation, Analysis of Alternatives	Pre Key Decision Point activities Requirements document, Concept of Operation, Analysis of Alternatives report	Conceptualize
Milestone A Technology development	Key Decision Point-A Study phase, ends with System Requirements Review	Develop
	Key Decision Point-B (Program Initiation). Design phase (System Design Review, Preliminary Design Review & Critical Design Review)	
Milestone B (Program Initiation); System development and demonstration (starts system integration sub-phase)		
Mid-phase design readiness review (starts system demonstration sub-phase)	Key Decision Point-C Build phase (Critical Design Review, build, test launch, support)	Operational Test & Evaluation
Milestone C (Low-Rate Initial Production decision); Production and Deployment phase	"Follow-on Buy" or Low-Rate Initial Production decision as appropriate	Transition to Operation
Milestone Decision Authority Review; Full rate production decision	Major upgrade decision or full rate production decision as appropriate	
		Operate, maintain, enhance
		Disposal

Two major observations result from the mapping for the life cycle phases. NSS 03-01 and ISO/IEC 15288 begin and end at similar stages which make them relatively compatible. But upon closer inspection, it is evident that the mapping is not balanced between the two life cycles especially in the *System Development* and *Transition to Operation* phases. This is not critical since the entry and exit points are similar. But care must be taken when estimates are decomposed by life cycle phase which is often done by defense contractors hired to only participate in portions of the system life cycle. In a similar way that systems engineering can be estimated by activity, we show how space systems can be estimated by program phase based on data obtained from the COSYSMO repository.

C. Partial Estimation of Systems Engineering Effort by Phase

The estimate provided by COSYSMO can be distributed by life cycle phase for better planning and management of systems engineering activities throughout the life cycle. The assumption in the model is that a standard set of systems engineering activities are being performed throughout certain phases in the life cycle. This typical spread is provided in Table 5. This distribution is not universal but it provides a typical spread of effort that is characteristic of systems engineering projects.

Table 5. Systems Engineering Effort Distribution Percentage Across ISO/IEC 15288 Phases

Conceptualize	Develop	Operational Test & Evaluation	Transition to Operation
23	35	28	14

To illustrate its application for adjusting a systems engineering estimate, consider the following example. With A_1, A_2, A_3, and A_4 representing the distribution across life cycle phases, the sum of the four life cycle phases equals the total systems engineering estimate, that is:

$$\sum_{i=1}^{4} A_i = 100\%$$

Therefore, the COSYSMO estimate (x) can be allocated across each of the four life cycle phases.

x * 0.23 = effort needed in A_1
x * 0.35 = effort needed in A_2
x * 0.28 = effort needed in A_3
x * 0.14 = effort needed in A_4

TOTAL = x

The breakdown of effort by systems engineering life cycle phase is helpful not only for resource management purposes but also when an organization is only interested in estimating part of the systems engineering life cycle. For example, if the systems engineering organization is only responsible for the *Conceptualization* (A_1) and *Development* (A_2) of the system then the typical effort can be calculated as a function of the adjusted effort factor as follows:

$A_1 + A_2$ = adjusted effort factor
0.23 + 0.35 = adjusted effort factor
0.58 = adjusted effort factor

The initial estimate provided by COSYSMO, x, should be adjusted by a factor of 0.58 to reflect the absence of the *Operational Test & Evaluation* (A_3) and *Transition to Operation* (A_4) life cycle phases assumed in the estimate.

V. Implications

In addition to making COSYSMO more relevant to space systems, this work has two important implications. The first is that it enables comparison to a normative effort profile. This helps determine the progress of a program from an earned value management perspective. Such resource tracking can serve as a leading indicator for program performance based on a relative determination on whether a program is behind schedule. For example, COSYSMO provides an effort profile that indicates the typical systems engineering effort needed for the development phase of a program is approximately 35%. If a program or effort estimate drastically deviates from this, it would warrant further investigation.

The second implication is that the additional level of granularity in the effort estimate can aid in the piecemeal estimation of systems engineering effort. Following the previous example, the systems engineering effort can be adjusted to include only the life cycle phases being performed. If an organization is only concerned with the “up front” systems engineering needed for a program, the total systems engineering effort can be proportionately adjusted by the appropriate effort factor.

VI. Conclusion

In light of the high cost of space systems and high rate of cost overruns[15], there has been a critical need to revitalize systems engineering throughout the life cycle.[16] We can approach this goal by using better tools and techniques to estimate systems engineering effort such as COSYSMO. But the model alone is not sufficient; it must be tailored to the space systems domain so that its relevance can be improved.

We have shown that the systems engineering activities and life cycle phases can be mapped to prototypical equivalents in the space systems domain. This mapping serves as a normalization so that the existing version of COSYSMO can be used to evaluate systems engineering estimates in the space domain. Moreover, by providing a technique to do partial activity and life cycle phase estimation we provide additional level of granularity that can help improve the accuracy of systems engineering estimates.

Ultimately, these methods should be validated by each organization since the percentages provided could vary depending on organizations and domains. Specifically since the discussion has been a US-DoD centric analysis. We expect this approach to be useful to similar organizations and technical domains wishing to improve their systems engineering cost estimation capabilities.

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